

<p style="text-align: center;">NSTRF Research Training Plan for NASA Grant #NNX11AM61H</p> <p style="text-align: center;">Modeling Cable-Harness Effects on Spacecraft Structures</p> <p style="text-align: center;">Virginia Polytechnic Institute & State University</p>	
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Mentor	Gregory Agnes Jet Propulsion Laboratory

Abstract

As spacecrafts become more lightweight as a result of advances in material technology, the cable harnesses and wiring are making up a greater percentage of the spacecraft's mass. Prior investigations are finding that this mass, which was once just lumped into the total mass of the structure, may be affecting the dynamic response of the craft. The goal of this research is to investigate the effects of cable harnesses on spacecraft structures. More specific and measurable goals will be outlined after a meeting of the student, advisor and mentor in February of 2012 to focus the research. In the meantime, the student has identified possible topics of interest, performed basic experiments to investigate the challenges in gathering data and modeling, and is beginning to develop experiments to be performed at JPL in the coming year. Challenges include characterizing the contact interaction of the cables in the cable harness, maintaining a free-free boundary condition to simulate the lack of gravity in space, and determining a way to effectively model the damping inherent in the system. The student will be using mathematical methods as well as experimental investigation to approach the problem, and hopes to develop mathematical models that can be validated by the conducted experiments. Although expected outcomes will be determined once the student and committee meet to narrow the focus of the research, a guaranteed outcome will be a greater understanding of the effect of cable harnesses on structural components. By learning more about the interaction of these materials, modeling of space structures will be improved.

Research Description

Introduction

The future of space structures involves the use of lightweight structural elements. These lightweight materials are obviously beneficial in terms of reducing the overall weight to launch, but as the spacecraft mass decreases, the cable harnesses and wiring that surround the object make up a greater proportion of the object's mass. Since the control system technology for spacecraft is also developing, requiring more signals and electrical paths, these complex systems mean that an extensive wiring system is required on any given spacecraft, and robust cable harnesses are unlikely to disappear anytime soon. Thus, cable harness mass is becoming a significant structural component of spacecraft structures.

Because these cable harnesses now make up a significant percentage of structure mass for satellites and other spacecraft structures, the Air Force Research Lab (AFRL) at Kirkland Air Force Base has identified the problem of cable harness effects on satellites as being extremely significant for vibration modeling. A more complete understanding of the interaction between the cable harness and the shell of a spacecraft must be developed in order to correctly program control systems, eliminate unnecessary vibrations, and ensure the structural integrity of the spacecraft. In addition, current and future space structures may be too large and too flexible outside of a vacuum to be tested before their launch, so it is imperative that models of these structures be accurate and take into account the growing mass percentage of the cable harness, not as a lumped mass, but as a structural element that can affect the motion of the spacecraft. Based on the questions posed by the AFRL, I (the student) will be investigating the effects of cable harnesses on spacecraft structures.

Goal

The goal of this research is to develop a scientific basis for characterizing the effect of power and signal cables attached to lightweight, flexible spacecraft structures in order to develop models of such systems to gain understanding of the important physical effects that affect their dynamic response. At this time, the project goal is still very broad; more specific and measurable goals will be developed in collaboration with the NASA mentor and student's advisor in February 2012, after extensive reading and research is done from November 2011-January 2012 to determine what is needed and what is achievable.

Background

As listed in the reference section, the Air Force Research Laboratory has written several papers on the subject of cable harness effects, and some similar experiments have been performed at JPL. Before learning of JPL's efforts, experiments were conducted at Virginia Tech to start investigating the problem and determine what challenges may arise. The Air Force Research Laboratory ran cable-only tests to determine the parameters of the cables used, and found that the cables could nearly be described by Euler beam theory, but that they were non-linear elements. From background reading, the specific tie down type was determined, as well as types and construction of the cables to be tested. The cables tested at Virginia Tech were basic electrical

wires, and JPL should be able to provide cable material that more closely matches that which would be found on space structures. From the AFRL work, the student learned that cable parameter estimation would be a good starting point, and that there were plenty of questions and challenges still to be answered and met in this investigation. The student decided to set up an experiment to compare the results of a cabled beam to a bare beam, and then to an analytical model developed in collaboration with other students. Figure 1 is a representative graphic of the work done at the CIMSS Lab at Virginia Tech to date; it shows a close up view of a “cable” (in this case, a copper rod) attached to a narrow beam, with the response of the cabled beam at this point for the beam-rod system and for four other beam-cable systems shown in the plot at the top of the image.

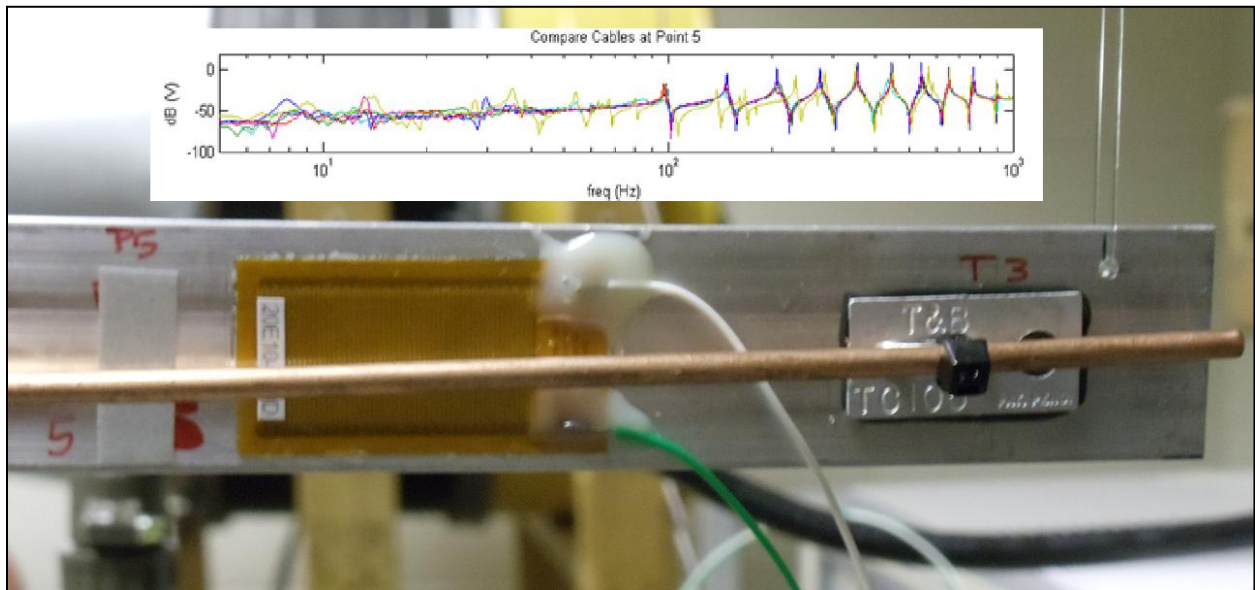


Figure 1. Representative graphic showing a close-up of the piezo-excited cabled beam at point five along with the response results for this configuration overlaid on top.

Approach/Methodology

As noted, the student has already begun experimental testing of the cables and the cable-beam system. The approach/methodology section will be divided into work performed to date and future work to be performed.

Approach/Methodology: Work Done to Date

The first step was to determine the characteristics of the cables that were being used for the cabled beam experiments. It was decided to use cables that could be readily obtained in the lab for these preliminary experiments as a way to determine if the method was sound before spending time and money on space-worthy cables. In order to measure the response of the cables, each cable was clamped between two vices at a specific tension. Most cables were tested at tensions of 0, 1, 5, 10 and 20 pounds. A shaker device was set against the cable and the cable was lightly taped to the flat surface of the shaker to ensure that the cable did not bounce away from the shaker and that the cable's motion input was indeed the shaker output. Rather than trust

the shaker's readings, a laser vibrometer was set up to measure the motion of the shaker while a second laser vibrometer was trained on the cable and moved from point to point to take readings at various points along the cable. Figure 2 shows the cable parameter set up, with one red cable in the vices with the shaker attached, the additional cables on the lab bench, and the two laser vibrometers in their positions.

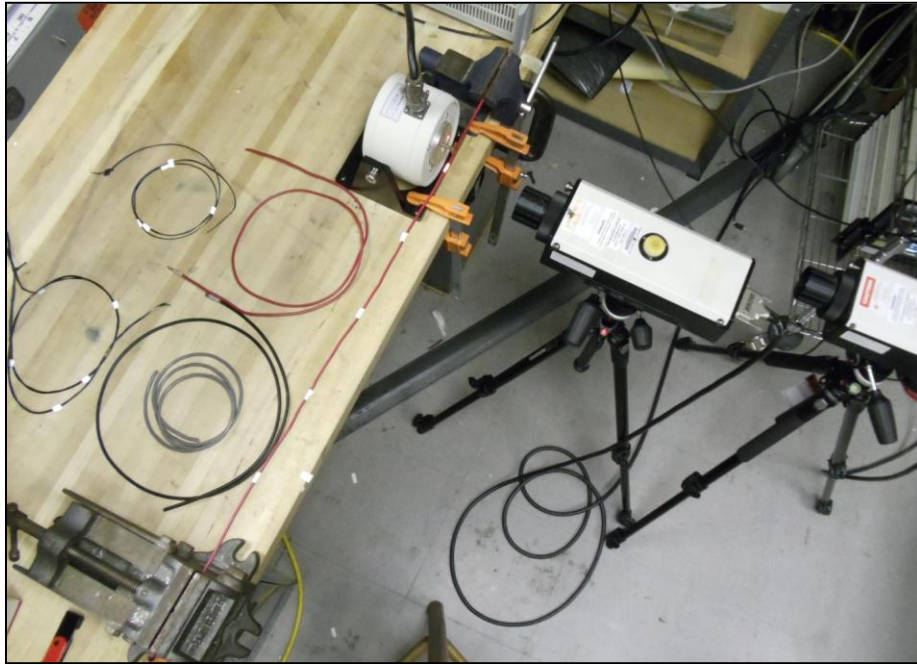


Figure 2. Laboratory set up for cable parameter testing.

Once cable parameters were determined, cables were attached to a beam with TC-105 tie-downs as recommended in the AFRL papers. The cables were tied down at 3, 5, 7 or 9 attachment points and the beam was excited by the use of a piezoelectric patch at one end that excited the beam with random noise. Figure 3 shows the cabled beam test set up; the beam is hanging from the ceiling with no horizontal constraints in order to simulate the free-free condition that would be typical for space structures.

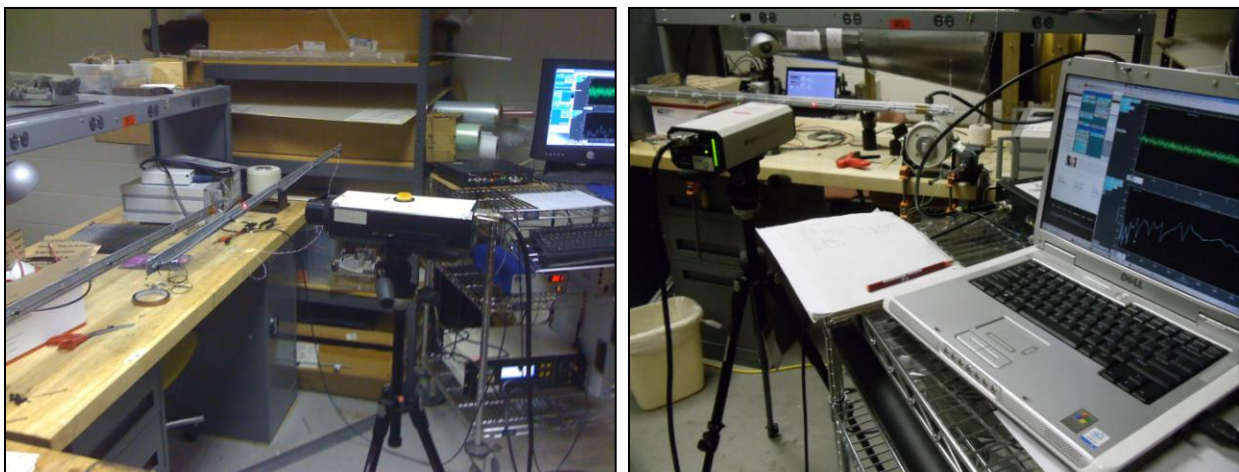


Figure 3. Test set up for the cabled beam.

Once cabled beam data was analyzed and compared to a finite element model, the results were close but not exact. Since there was some ambiguity on whether a thin cable such as the ones used in these experiments should be modeled as a string or as a rod, a copper rod was procured and attached to the beam in the same manner as the cables, and the same tests were run. Figure 4 shows the rod attached to the beam with the orange piezoelectric excitation patch, and figure 5 shows the entire rod-beam system.

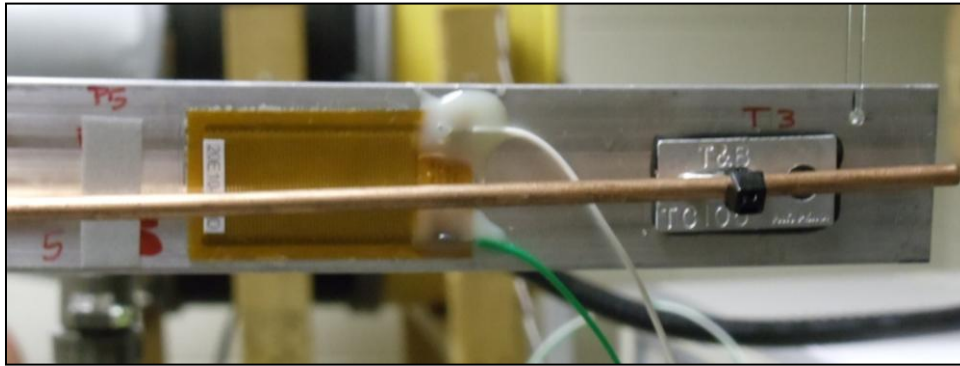


Figure 4. Rod-beam system at point 5 showing piezoelectric patch and tie-down detail.



Figure 5. Rod-beam system with three tie-down points.

Data was taken through SigLab, a data acquisition program, and processed in Matlab to compare the different cables and attachment points. Unfortunately low frequency responses (below 100 Hz) were erratic and did not necessarily agree well from cable to cable; despite running multiple tests, trying to keep the set up as controlled as possible, and adjusting the laser vibrometer and data system, better low frequency data could not be obtained, perhaps likely due to the low frequency resonance of the strings used to hang the beams from the ceiling and air currents and other activities in the lab and in the building. Hopefully this will be an aspect of testing that can be mitigated at JPL as they have more isolated testing rooms. The results for frequencies between 100 and 1000 Hz were much clearer and matched well from system to system. The rod-

cable system behaved significantly differently than the cabled-beam systems, which were quite close to the response of the bare beam. From these results, a program to measure the damping at each frequency was developed as well. Figure 6 shows the overall results for the bare beam, cabled-beam systems and rod cable system at each point for three tie downs.

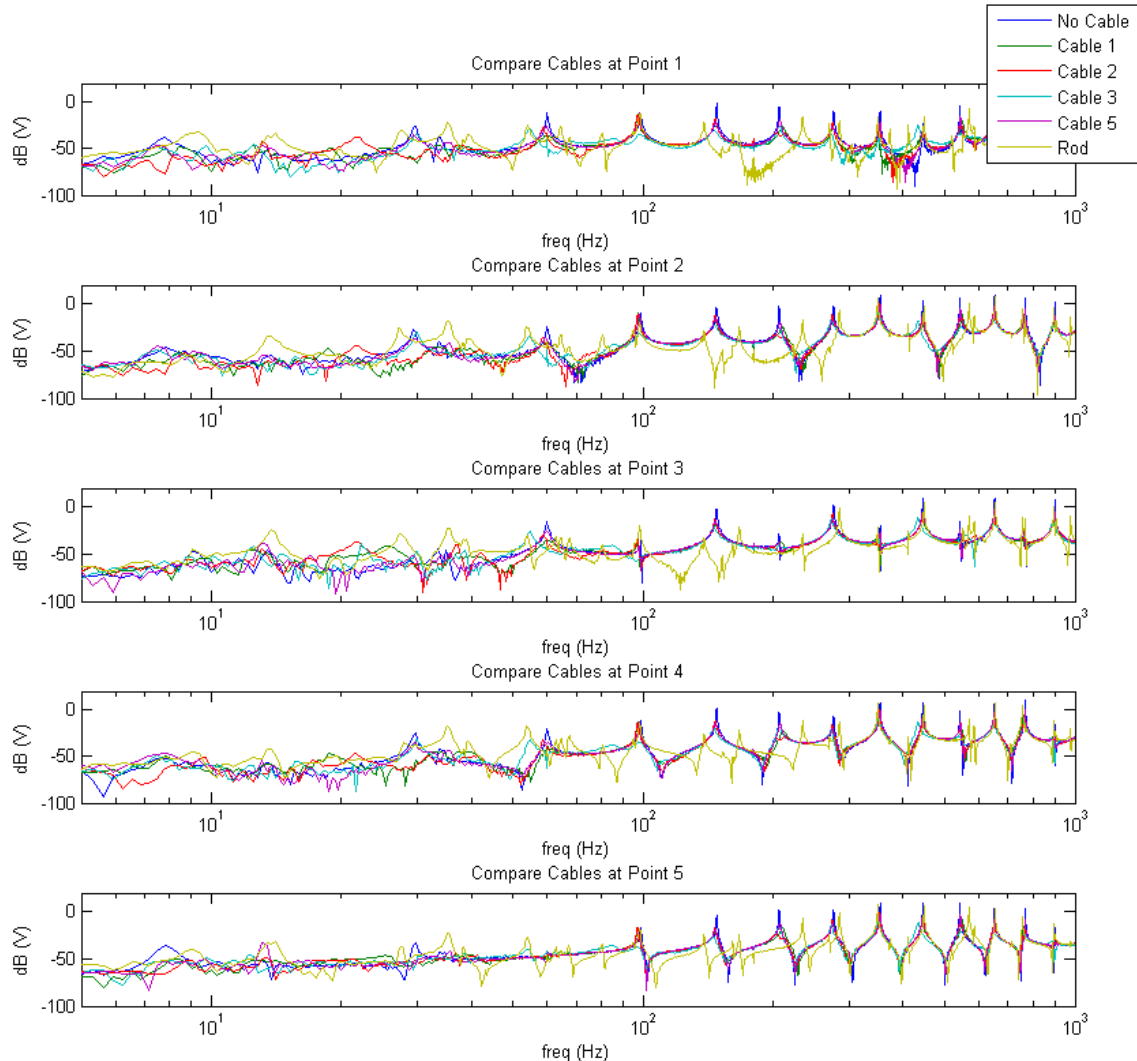


Figure 6. Overall results for three tie-downs; four cables, rod and bare beam compared at points 1 through 5.

Figure 7 (on the next page) shows the results at point two so that the agreement between the cabled beams and the bare beam can be seen more clearly. The rod (shown in mustard yellow) has a significantly different response. Figure 8 (also on the next page) shows the response at each point for cable two for the four different tie-down configurations (three, five, seven and nine).

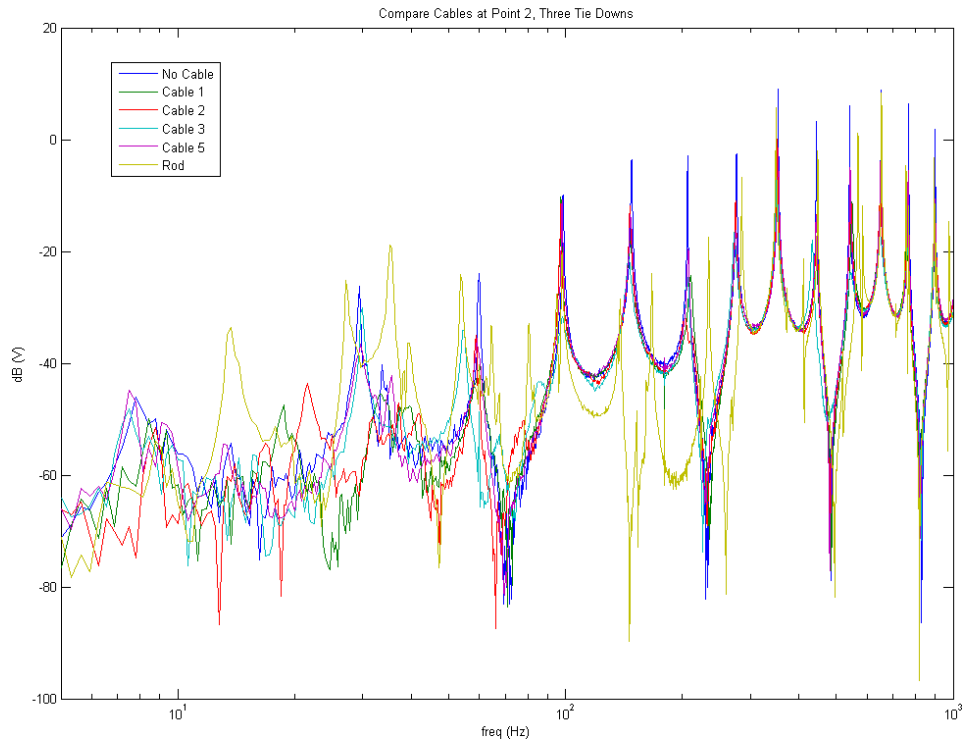


Figure 7. Comparison of cables, bare beam and rod at point 2 for three tie-downs.

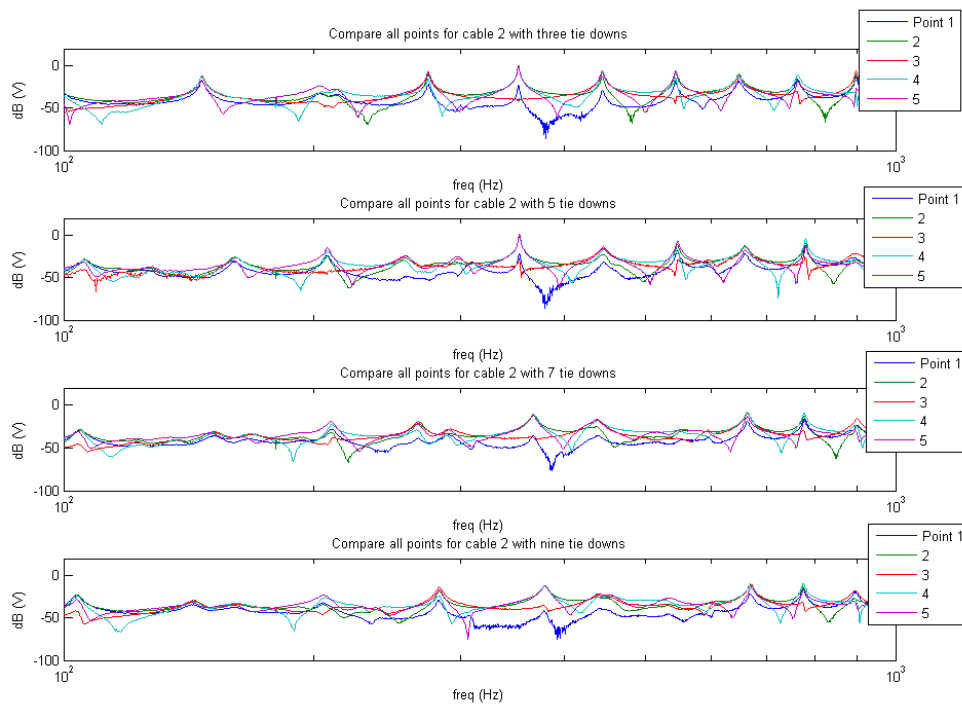


Figure 8. Comparison of points for cable 2 for three, five, seven and nine tie-downs.

Figure 9 and 10 show the variation due to different tie down configurations for cable 1 and cable 2 at point 5 on the beam.

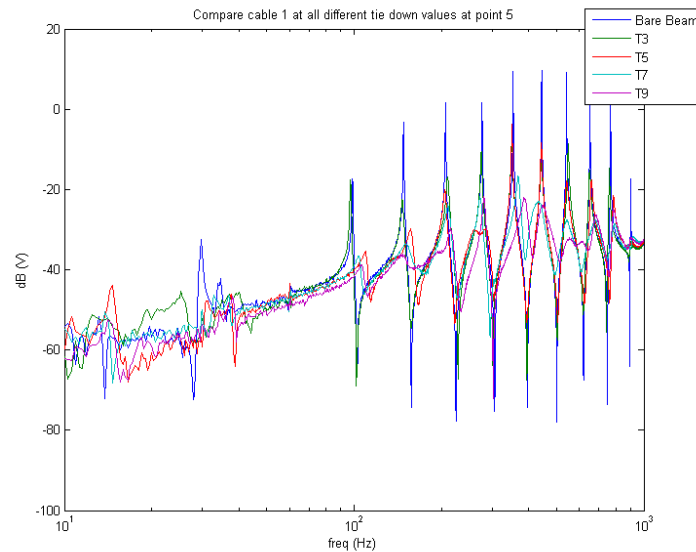


Figure 9. Comparison of different tie-down configurations to bare beam for cable 1 at point 5.

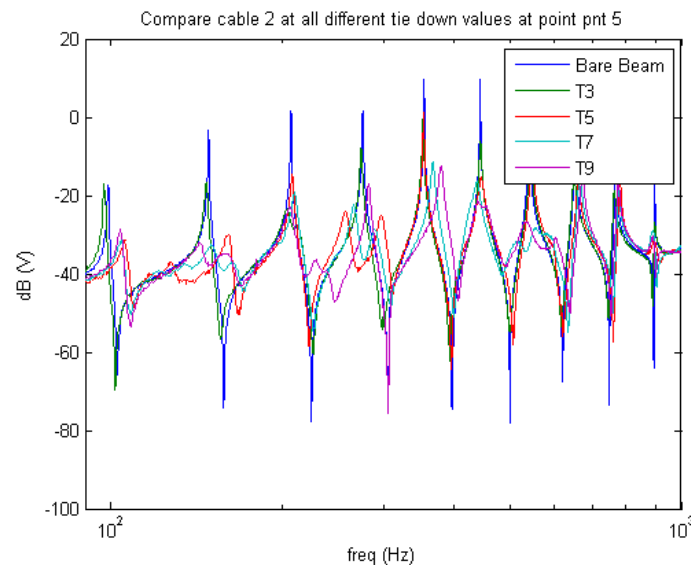


Figure 10. Comparison of different tie-down configurations to bare beam for cable 2 at point 5.

The tests were consistent from trial to trial and showed that the number and spacing of the tie downs changed the system response as well as the type of cable and the specific point at which the measurement was taken. With so many variables, a lot of data was collected as part of the student's goal of creating a database of baseline experimental responses, but it seems as though reducing the number of variables or studying one set of changes at a time would be more conducive to producing relevant results.

Approach/Methodology: Work To Be Done

The experiments that have been conducted so far were primarily useful in determining what

parameters are worth investigating and developing methods to run meaningful experiments with accurate data. Now that I will be at JPL for the next few months, the experiments can be run in a more controlled environment with actual space cables.

On the experimental front, the method used for the testing at Virginia Tech gave reasonable results; hopefully, using the more controlled testing environment at JPL will help to make the lower frequency results less volatile. Another option is to consider using a simply supported beam to see if the low frequency issues are related to the mechanism used to hang the beam to simulate the free-free condition. An additional benefit to working at JPL is that cables that are spacecraft appropriate and properly wrapped will be used for all future experiments.

The student will again start with cable property testing, but this time it will be with much thicker cable bundles. There has been some discussion as to whether the contact mechanics of the interaction between the individual cables should be investigated, so some of the reading and research scheduled for January 2012 includes contact mechanics. The AFRL papers discuss their cable property testing in detail, so there should be similarity between the tests. This test should also confirm the type of model used to describe cable elements, be it Euler beam theory or shear beam theory or even something entirely different.

Once cable property testing is done, the cables will be attached to beams and experiments run to measure the response of the cabled beams. If the Virginia Tech testing is any indication, there should be minimal variation in the frequencies of the beams, but significant damping at each frequency, which should be quantified. By measuring the damping of the various cable configurations, some insight will be gained into the effects that the cable harnesses have. If time permits and if all testing goes well, the next logical step would be to attach cable harnesses to a structure rather than a beam and see if the same trends hold. The AFRL did this for a plate, which was largely unsuccessful due to the lack of continuity through the material, and for a rectangular truss structure, which was more successful.

In addition to the experimental work to be performed, a proposed goal for the project was analytical models to describe the motion that could be validated by the experimental data. The experimental data will be gathered at JPL, and analytical models will be developed simultaneously. The first model is based on homogenization, which takes advantage of the repeating pattern of cable attachment points. Homogenization can be used if the cable attachment points are identically spaced, forming identical elements, and will be combined with continuum modeling to produce low order, accurate models. These models are superior to finite element methods because of the lower order form obtained without sacrificing accuracy. The homogenization method will allow me to calculate simple partial differential equation models of the cabled beams by matching the energy of each element to that of a fundamental beam model. A linearly varying displacement field will be used to determine the strain components. The strain energy will be calculated from these components and variational principles will be applied to equate this expression to the equations of motion of an equivalent beam model.

Further investigation will include models developed through the theory of combined dynamical systems, and finite element analysis with model updating methods. The combined dynamical systems method combines the distributed parameter portions of the system (the structure and

cables) with lumped parameter portions (the tie downs or attachment points). Using singularity and Green's functions, a modeling description of the system is obtained. Model updating involves an existing finite element model, which will be compared to the experimental data collected for the current proposal. By inspecting the differences between the model and the experiment, algorithms can be developed to match the model more closely to the real-life results. This method could be a very good application for this project since the damping effects are as yet poorly understood; model updating is a good way to account for these constant effects without fully modeling them.

Previous research undertaken by the AFRL indicates that cable harnesses behave like a beam rather than a string, and that shear effects must be taken into consideration. Some research has been done on beam-beam interaction, so this is where I will be starting for the fundamental beam model.

Expected Outcome(s)

The overarching goal of this research is to develop an in-depth understanding of cable effects on space structures. The specific deliverables and outcomes are to be determined by advisor, mentor and student in February. Ideally, the student will have developed models to describe the response of a cabled system, but since so little is known about the cable interactions and the damping mechanisms, it may be unrealistic to predict damping values and completely model the system response. Discussion with the mentor and advisor should help the student to determine what goals are achievable. As noted in the AFRL papers, modeling approaches for more complex structures whose response cannot be purely analytically predicted will need to be developed; this may be a case in which the experimental data collected throughout the year will be useful to provide baseline values for the effects of cable harnesses. As listed in my project proposal, ambitious goals include:

- A method of describing structural cable effects using beam homogenization, culminating in validated homogenization models of cable-harnessed structures

- A database of experimental results characterizing the dynamic response of cable-harnessed structures to vibration input

- A thorough understanding of experimental requirements and the ability to design and execute a sound and repeatable set of experiments to validate models

- Significant progress on methods of describing structural cable effects using the theory of combined dynamical systems and model updating for finite element analysis

- A basic understanding of cable effects

- At least two papers publishing the results of the homogenization modeling and experimental data collection

- A presentation of my findings at as many relevant conferences as is reasonable based on the findings

These outcomes will be discussed with the mentor and advisor in February; it seems likely that a few of these outcomes will be expanded and others discarded in order to narrow the project focus and make the outcomes specific and achievable.

References

Babuska, Vit, Douglas Coombs, James C. Goodding, Emil V. Ardelean, Lawrence Robertson, and Steven A. Lane. "Modeling and experimental validation of space structures with wiring harnesses." *Air Force Research Laboratory*. December 2010.

Goodding, J.C., et al, "Studies of free-free beam structural dynamics perturbations due to mounted cable harnesses," *48th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference*, Honolulu, HI, April 2007, AIAA Paper 2007-2390.

Robertson, L. M., et al, "Cable effects on the dynamics of large precision structures,"

48th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Honolulu, HI, April 2007, AIAA Paper 2007-2389.

Relevance to NASA

*[Description of how the proposed research is tied to NASA's Grand Challenges and Technology Area Roadmap(s). Identification and linkage to at least **one** Technology Area Breakdown Structure (TABS) element and to at least **one** Grand Challenge is required. Justification for relevancy should be provided for all ties identified.]*

Link to TABS: <http://www.nasa.gov/offices/oct/home/roadmaps/index.html>

Link to Grand Challenges:

http://www.nasa.gov/pdf/503466main_space_tech_grand_challenges_12_02_10.pdf

This section is expected to have significant input from the mentor in identifying and elaborating on the ties to not just the Technology Areas and Grand Challenges, but also documenting relevance to on-going activities in NASA's Mission Directorates.

This research aligns with NASA's mission directorates, and is specifically applicable to the Space Technology Roadmap (STR) Technology Area 12.2, Structures, with a secondary focus on TA 11.2, Modeling. The research involves lightweight space structures and design methods, should improve reliability, will develop test tools and methods, and may lead to further innovative concepts. Because my current research deals directly with space structures, it is easy to see that vibration of space structures would certainly come into play in the study of aeronautics and exploration structures, as any structure being propelled into space will experience vibration and is highly likely to have wiring and cables attached. However, my research will also be applicable to science and space operations. By understanding the vibration modes and effects of these space structures, we may eventually be able to harness some of that unwanted kinetic energy and use it to enhance the power system, providing energy to power sensors and further reducing cables, and thus, weight. In addition, most spacecraft and satellite control systems are dependent on knowing the motion of the object; by further refining our knowledge of spacecraft vibration, we should be able to more accurately model spacecraft and satellite movement, and thus improve the accuracy of space control systems and operations. In this respect, my research also supports TABS 11.2, Modeling, since it will involve software modeling, model checking, and science and engineering modeling. My research will contribute to the understanding of the dynamics of these systems, and will allow a greater degree of confidence in models for the systems used in exploration systems and space operations.

When it comes to the grand challenges, although this work may not seem transformative as yet, there is significant progress in the study of vibrations related to the field of piezoelectric materials, which can convert mechanical energy from vibrations into electrical energy. If the vibrations of spacecraft structures are well-understood and modeled, there may be a point at which this vibration information could be used to fit piezoelectric energy harvesters onto spacecraft to provide additional power without requiring additional power sources. This would support NASA's Grand Challenge of Affordable Abundant Power, since the information about vibration could be used to harness that kinetic energy and convert it to usable electricity via piezoelectric materials. This research is also relevant to the Grand Challenge of Efficient In-Space Transportation, as a better understanding of how a spacecraft is moving will allow us to

construct better control systems to more accurately and precisely move things around space.

On-Site Experience(s)

Rather than spend only ten weeks at a NASA research center, this research will be conducted primarily at the NASA Jet Propulsion Laboratory in Pasadena, California over a matter of months. Because the student has completed her qualifying exams at Virginia Tech and will complete her coursework in December 2011, she is able to spend the remainder of the program year (January-August) at JPL to conduct this research. This is advantageous for several reasons. First, JPL has also been looking into the issue of cabled-structure dynamics and will allow the student to benefit from knowledge and equipment already procured. Secondly, while the student has conducted some preliminary cable and cabled-beam testing at Virginia Tech, she has found that a more controlled testing environment would be advisable, as even small air currents in the testing area affect the free-free configuration that the testing requires. JPL has facilities for more controlled testing which the student will be able to set up and use. In addition, while the student has been using ordinary cables of various wiring types and sizes, at JPL she will have access to the actual cables used to send power and signals on spacecraft, as well as the cable-wrapping and production techniques used for actual spacecraft. This will make the research more directly applicable to NASA's devices and should yield the most realistic and useable data. Finally, by being immersed in a research center that focuses on research but also has elements of applicability, the student hopes that this research will be focused and as applicable as possible to real-world problems, specifically, NASA's grand challenges.

Conferences

- Virginia Space Grant Consortium Conference, April 2012, Virginia. Exact date and location to be determined. “Modeling Cable-Harness Effects on Spacecraft Structures.” As a recipient of a VSGC Fellowship, I will attend this conference to present my research as of March 2012.
- AIAA Structures and Dynamics Conference, April 23-26, 2012, Hawaii. Submission deadline has passed for the 2012 conference, but should consider 2013. “Modeling Cable-Harness Effects on Spacecraft Structures.” This conference combines aspects of aerospace with structural dynamics, which aligns perfectly with the current research. Would expect to attend this conference annually.
- Other conferences to be determined as advisor or mentor recommend as research further develops.

Schedule

Milestone or Activity	Estimated Date(s)
<i>Began graduate degree coursework at Virginia Tech</i>	<i>August 2010</i>
<i>Passed Ph.D. Qualifying Exam</i>	<i>March 2011</i>
<i>Preliminary experiments at Virginia Tech conducted</i>	<i>June-August 2011</i>
<i>Completed degree-required coursework</i>	<i>December 2011</i>
Background reading of contact mechanics, prior research, AFRL research, and beam-cable interactions. Determine areas of greatest concern and interest, identify challenges and strategies to overcome obstacles.	November 2011-Jan/Feb 2012
On-site experience at Jet Propulsion Laboratory, California	January-August 2012
Meeting with advisor and mentor at JPL to finalize project direction, goals, and deliverables. Determine specific goal and research question to be answered.	Early February 2012
Design of experiments to be conducted	February 2012
Conduct experiments, develop model	February 2012-March 2012
Data analysis and model validation	March 2012-April 2012
Consider committee meeting for research update	March 2012
Technical presentation at VSGC conference, Virginia	April 2012
Attend AIAA Conference	April 2012
Determine further experiments needed, synthesize conference and committee meeting feedback, outline and write thesis rough draft	May 2012

Conduct experiments, (round 2), improve model	June-August 2012
Data analysis and model validation, writing	September-October 2012
Preliminary thesis defense	November 2012
Finish any outstanding work, complete thesis	December 2012- January 2013
Degree conferred, graduation	May 2013